
THE
INCREMENTAL PERMEABILITY METHOD
FOR THE MAGNETIC ANALYSIS
OF HIGH SPEED STEEL

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DISSERTATION

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VITA

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From September 1924 to October 1925, he was employed by the Westinghouse Electric and Manufacturing Company, taking the Student Course in Meter and Relay Operating.

He returned to the Johns Hopkins University in October 1925, as a graduate student in Electrical Engineering, where he has studied under Professor J. B. Whitehead and Associate Professor W. B. Kouwenhoven. During the summers of 1926 and 1927 he was employed by the Bell Telephone Laboratories, Inc., in New York City.



THE INCREMENTAL PERMEABILITY METHOD FOR THE MAGNETIC ANALYSIS OF HIGH-SPEED STEEL

By W. B. KOUWENHOVEN¹ AND JULIAN D. TEBO²

SYNOPSIS

This paper describes a new method of magnetic analysis which the authors have called the incremental permeability method. It uses two magnetomotive forces simultaneously, and the change in induction produced by the superimposed or incremental magnetomotive force in the specimen is measured. This superimposed magnetomotive force may be produced by direct or alternating current.

The magnetic properties of high-speed tungsten steel bars were investigated using this method and data were obtained which makes it possible to differentiate between the heat treatments received by the specimens.

INTRODUCTION

The purpose of this investigation was to test a new method of magnetic analysis, which the authors have called the incremental permeability method, and to determine what relation, if any, exists between the magnetic properties as found by this method and the heat treatment of high-speed steel. The object was to correlate certain magnetic characteristics of the specimens with their heat treatments. The work was done in the electrical laboratory of the Johns Hopkins University, under the auspices of the Society's Committee A-8 on Magnetic Analysis. Previous investigations have been made by this committee on high-speed steel twist drills (1).³ Numerous tests have been made by other investigators (2, 3, 4, 5, 6, 7, 8) on the specimens used in the present investigations.

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³ The boldface numbers in parentheses refer to the papers given in the list of references appended hereto.

INCREMENTAL PERMEABILITY METHOD

The incremental permeability method of magnetic analysis uses two magnetizing forces simultaneously on the same specimen. A fixed magnetizing force of some predetermined value, F_F , is first applied to the specimen and then a second magnetizing force, ΔF , called the incremental force is superimposed upon F_F and the increment or change in magnetic induction, ΔB , produced by ΔF is noted. The fixed magnetomotive force, F_F , is produced by a continuous current. The incremental magnetomotive force, ΔF , may be positive, that is, in the same direction as F_F ; or negative, that is, opposing F_F ; or it may be an alternating magnetomotive force.

It is a well-known fact that the shape of the hysteresis loops for specimens of the same chemical composition depend to some extent upon the heat treatment received by the specimen. It is also true, however, that slight changes in the drawing temperature for specimens of a given quench often produce such small changes in the maximum induction, residual magnetism, and coercive force as to make it impossible to differentiate between two specimens which had received different heat treatments. It was therefore decided to attempt to separate specimens that had received different heat treatments by using superimposed magnetizing forces, or an incremental permeability method, as it has been named.

This investigation may be divided into the following sections:

1. Development of apparatus and procedure for applying the incremental permeability test to specimens.
2. Determination of the best values of constant magnetomotive force, F_F , and the superimposed magnetomotive force, ΔF , which will separate specimens whose hysteresis loops overlap at the cardinal points, by giving different changes of induction ΔB .
3. Analysis of the results.

SPECIMENS

The specimens used in this investigation were made from high-speed steel obtained from the Horne Steel Products Co., and the heat treating and preliminary work was done under the direction of Mr. Thomas Spooner (2), of the Westinghouse Electric and Manufacturing Co. The bars from which the specimens were cut were $\frac{1}{2}$ in. square and were supposed to be all from the same heat. Each bar was assigned a letter and then cut into specimens approximately 10 in. long, each specimen being given a number in the order in which it was cut from the bar. The markings on some of the bars could not

be deciphered or had been omitted, and these bars were marked with the letter X. The specimens were ground to 0.45 in. (1.14 cm.) square and then normalized at 1650° F. (899° C.)

In the early magnetic tests of the normalized bars certain specimens marked *K* differed from the others. The cause of this was found to be due to a difference in the chemical composition of the *K* specimens as shown below:

	CARBON, PER CENT	SILICON, PER CENT	SULFUR, PER CENT	PHOS- PHORUS, PER CENT	MAN- GANESE, PER CENT	NICKEL, PER CENT	CHRO- MIUM, PER CENT	VANA- DIUM, PER CENT	TUNG- STEN, PER CENT
Normal Material.	0.79	0.42	0.042	0.031	0.176	0.10	3.46	0.88	17.35
<i>K</i> Sample.....	0.70	0.30	0.030	0.021	0.173	0.11	3.97	1.49	14.03

TABLE I.—HEAT TREATMENT OF BARS.

Drawn at		Quenched at 2109° F. (1154° C.)			Quenched at 2211° F. (1211° C.)			Quenched at 2316° F. (1268° C.)			Quenched at 2366° F. (1296° C.)			Quenched at 2419° F. (1326° C.)		
deg. Fabr.	deg. Cent.	Bar	Length		Bar	Length		Bar	Length		Bar	Length		Bar	Length	
			in.	cm.		in.	cm.		in.	cm.		in.	cm.		in.	cm.
No draw		B-2	10.00	25.4	A-10	10.06	25.7	K-3	9.53	24.2	D-6	9.00	22.9	J-4	10.00	25.4
		F-6	10.09	25.8	F-4	10.00	25.4	F-3	10.03	25.7	F-2	9.50	24.2	X-9	10.06	25.7
1000	538				K-4	9.47	24.1	A-12	10.06	25.7	A-4	9.82	24.9			
		C-6	9.41	23.9	L-7	9.50	24.2	L-6	9.44	24.0	B-5	10.00	25.4	I-5	9.50	24.2
		L-11	10.09	25.8	G-14	9.38	23.8	G-9	10.06	25.7	G-6	9.70	24.6	X-11	9.31	23.6
1050	566	G-5	9.44	24.0	B-4	10.06	25.7	B-10	9.41	23.9	L-1	9.60	24.4	K-2	9.47	24.1
		K-8	8.94	22.7	C-7	9.00	22.9	C-9	9.47	23.9	H-4	9.41	23.9	X-15	10.09	25.8
		X-5	9.50	24.2	H-10	9.47	24.1	H-8	10.03	25.7	X-6	9.38	23.8	L-4	9.44	24.0
1100	593	H-11	9.91	25.2	X-1	10.06	25.7	X-14	10.09	25.8	E-7	8.91	22.6	G-2	9.47	24.1
		D-14	10.00	25.4	L-10	9.97	25.3	D-7	8.40	21.3	X-12	9.44	24.0	H-5	8.91	22.6
		I-11	9.47	24.1	D-8	10.06	25.7	I-6	9.47	24.1	K-1	8.75	22.2	X-17	10.06	25.7
1150	621	X-23	10.06	25.7				X-16	10.06	25.7	I-1	9.87	25.1	X-2	9.53	24.2
		J-14	9.63	24.5	J-3	10.00	25.4	J-6	9.44	24.0	X-13	10.09	25.8	X-7	8.91	22.6
		E-10	10.03	25.7	X-26	10.03	25.7	E-6	10.06	25.7	C-5	8.89	22.6	X-19	10.00	25.4
		X-24	10.06	25.7	E-8	8.89	22.6	X-22	10.09	25.8				E-1	9.30	23.6

HEAT TREATMENT

After normalizing, 75 of the bars were quenched, 15 for each of the following temperatures: 2109° F. (1154° C.), 2211° F. (1211° C.), 2316° F. (1269° C.), 2366° F. (1296° C.) and 2419° F. (1326° C.). Twelve bars of each quench were then drawn in lots of three each at the following drawing temperatures: 1000° F. (538° C.), 1050° F. (566° C.), 1100° F. (593° C.) and 1150° F. (621° C.). In the final state there were thus three bars for each pair of drawing and quenching temperatures.

The heat treatments were made in a salt bath under carefully controlled conditions. The mean temperatures are believed to be

correct to within $\pm 3^\circ \text{ F.}$ (1.5° C.) with a maximum variation of $\pm 8^\circ \text{ F.}$ (5° C.), the average variation being less than half of this amount.

The heat treatment was completed approximately eight months before the work described in this paper was started and it is safe to assume therefore that there should be no uncertainty due to aging effects.

The bars available for this investigation and their heat treatments are given in Table I.

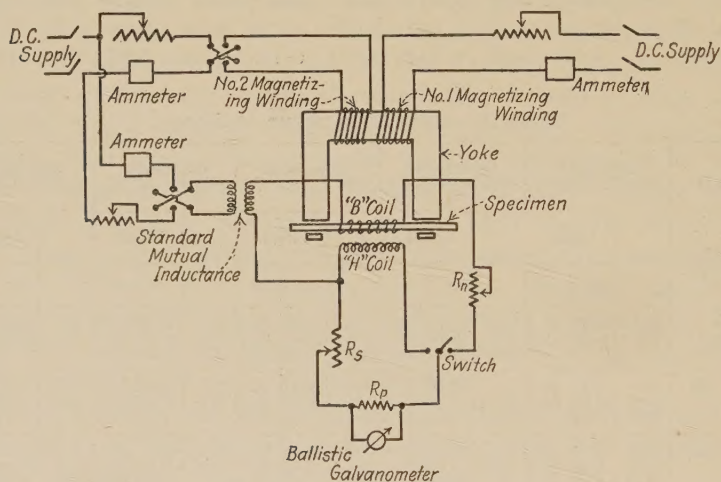


FIG. 1.—Diagram of Connections for Direct Current Tests.

APPARATUS

Magnetic and Electrical Tests:

The magnetic tests applied to the specimens were as follows:

1. Continuous current positive incremental test.
2. Continuous current negative incremental test.
3. Alternating current incremental test.
4. Differential alternating current incremental test.

In addition, the resistance of some of the bars was measured using a Kelvin Double Bridge.

A special permeameter of the Fahy Simplex Type was constructed for use in the positive and negative continuous current tests. This special permeameter had two separate magnetizing windings as nearly alike as possible wound on a laminated silicon steel core. The connections are shown in Fig. 1, where F_F is furnished

by a 120-volt battery and ΔF by a 6-volt battery. It is important that the constant F_F be furnished by a relatively high voltage source with sufficient resistance in the circuit to limit the current to the desired amount. Under these conditions the application of ΔF makes only a small change in F_F and reduces the secondary inductive effects to a negligible amount. Oscillograms of the current and voltages induced in the circuits by the application of ΔF confirmed this statement.

In the alternating current incremental test a special solenoid 3 in. long was wound. This solenoid had two magnetizing windings each of 500 turns of No. 18 B. & S., D. C. C. wire and a third winding of 6000 turns of No. 36 enameled S. S. C. wire which served as a search coil. The core opening was $\frac{1}{2}$ by $\frac{1}{2}$ in. and fitted the specimens closely.

A special differential magnetic tester similar to that devised by Fahy⁽⁹⁾ was constructed for the differential incremental tests. This tester had, however, two magnetizing windings which were similar to those provided for the simplex tester described above. Tests of this permeameter showed that the two halves were nearly equal. Values of induction measured on the same specimen in the two halves of the instrument checked within 50 gauss in 10,000.

POSITIVE INCREMENTAL METHOD

The normal magnetization curves and the hysteresis loops of a number of different specimens were taken and examined for the most favorable point at which to apply the incremental magnetomotive force. These showed that the steepest part of the normal induction curve for the specimens occurred at a magnetomotive force of about 40 gilberts per cm. Tests were made, however, at values of F_F ranging from 30 to 75 gilberts per cm. and with a ΔF from 4 to 30 gilberts per cm.

A specimen was first demagnetized and then the F_F was applied through winding No. 2 of Fig. 1, reversed twelve times to bring the specimen into a cyclic condition and the induction, B , measured. Then the incremental magnetizing force, ΔF , was applied through No. 1 winding of the permeameter and the change in induction, ΔB , noted.

In the positive incremental method the maximum separation was found at a constant F_F of 38 gilberts per cm. and with a ΔF of 6 gilberts per cm. Three readings using these values were then made on each bar and the mean of these results were plotted as shown in Fig. 2. The lengths of the lines connecting the points indicate the

spread of values of the induction B for F_F and the increment ΔB in induction for ΔF . The B points are indicated by the blocks and the ΔB points by circles.

A study of Fig. 2 shows that there is an overlap in both the B and ΔB values for bars that had received no draw and which had been quenched at 2316, 2366, and 2419° F. (1268, 1296, and 1326° C.),

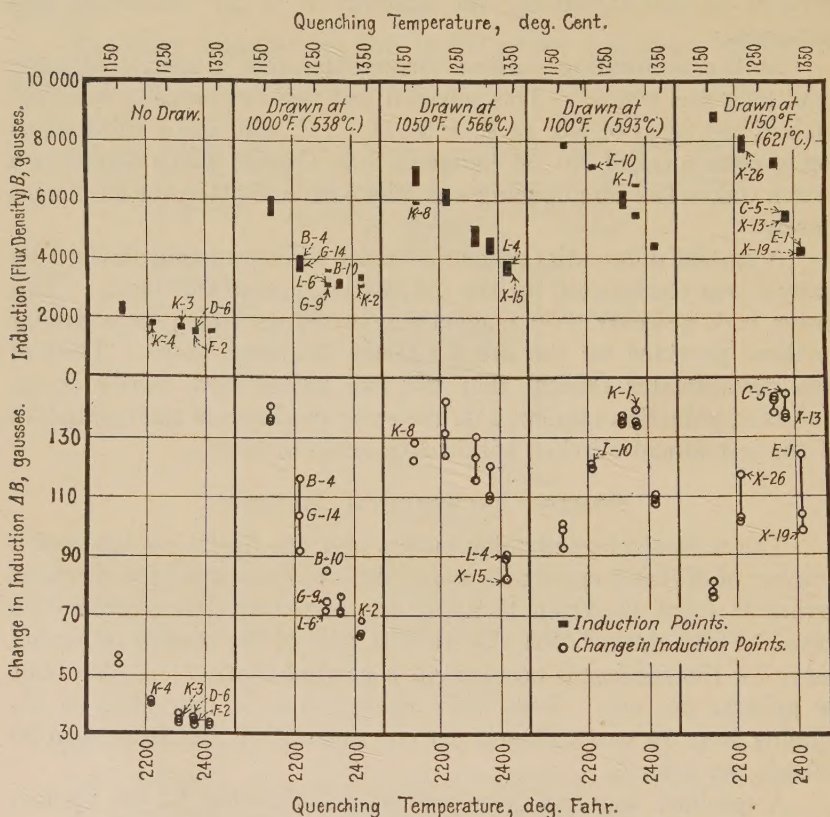


FIG. 2.—Results of Positive Incremental Test.

respectively, and there is also considerable overlap at the 1000 and 1050° F. (538 and 566° C.) drawing temperatures and 2316 and 2366° F. (1268 and 1296° C.) quenching temperature.

It is interesting to note that at the value of ΔF used in this test, the resulting increment in induction, ΔB , is to a large extent independent of the chemical composition of the specimens as shown by the position of the K bars. This, however, does not hold true at other values of ΔF .

NEGATIVE INCREMENTAL METHOD

In this method the same general procedure was followed as for the positive incremental method, except that ΔF was made negative and was larger than the constant F_F . The best values of F_F and ΔF in this case were found to be 106 gilberts per cm. and -138 gilberts per cm., respectively. The investigation covered a range in F_F from 50 to 150 gilberts and in ΔF from -4 to -150 gilberts per cm.

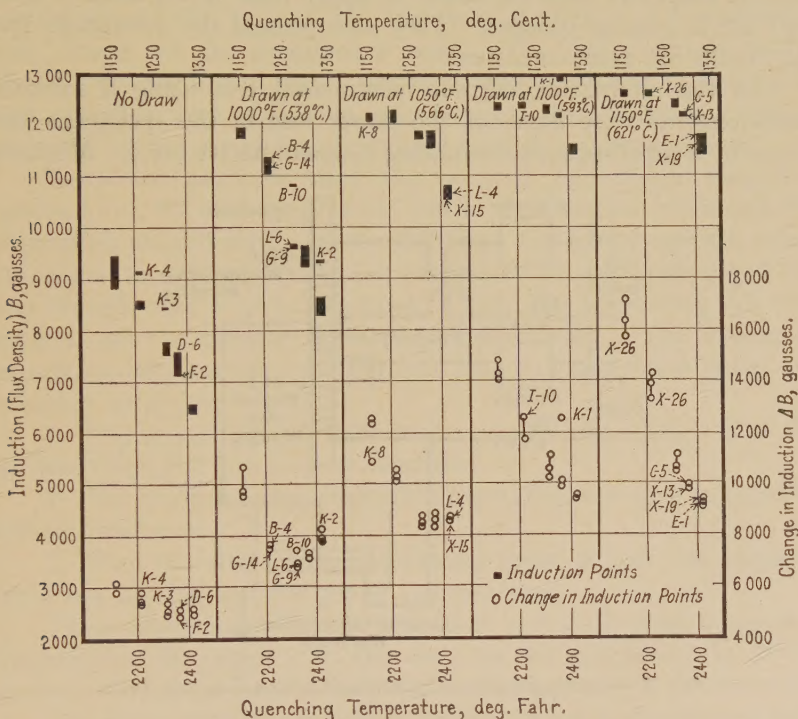


FIG. 3.—Results of Negative Incremental Test.

Three readings were taken on each bar with the above values of F_F and ΔF , and the agreement between individual readings is much better than in the positive incremental test. The mean values of B and ΔB for each specimen are plotted in Fig. 3. Comparing this with Fig. 2 it can be seen that at the higher values of induction used in this test there is less spread between the individual specimens of a given heat treatment. The K bars, however, do not line up with the others of the same heat treatment.

A study of Fig. 3 shows that the overlapping still occurs to some extent for specimens that were quenched at 2316 and 2366° F. (1268

and 1296° C.) and drawn at 1050° F. (566° C.) but that the separation of the other heat treatments is good.

ALTERNATING CURRENT INCREMENTAL METHOD

Solenoid Test:

It has been shown in previous investigations ⁽¹⁾ that alternating current magnetic tests are easier to apply than direct current tests, and are in general quicker. They also possess the advantage that the results are more consistent.

In the alternating current incremental test using a solenoid, measurements were made of the power loss in the specimens produced by a superimposed alternating magnetomotive force. Measure-

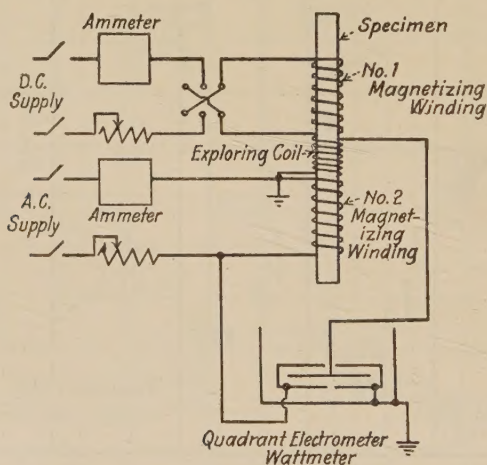


FIG. 4.—Connections for Alternating Current Solenoid Tests.

ments of the induced voltage in the secondary winding set up by the alternating ΔF were made on a few specimens, but the results were not promising. Therefore the voltage test was abandoned.

A quadrant electrometer, that was available, was used to measure the loss in the specimens. The connections for the test are shown in Fig. 4. The constant magnetomotive force, F_F , was supplied from a direct current source to the No. 1 winding of the solenoid and the alternating incremental magnetomotive force, ΔF , was applied to the No. 2 winding. The voltage circuit of the electrometer was connected to the secondary or exploring winding of the solenoid and the current circuit was supplied from No. 2 magnetizing winding. Although the readings of the electrometer with these connections

are not the true power loss in the specimens, we have called the quantity measured the power loss. With these connections the I^2R loss in the solenoid causes a deflection of less than one centimeter; therefore the loss in the solenoid had a negligible effect upon the results.

Test Procedure:

Two bars, *I-10* and *X-26*, both quenched at 2211° F. (1211° C.) and drawn at 1100° F. (593° C.) and 1150° F. (621° C.), respectively, were chosen for the preliminary work. The direct current incremental tests, see Figs. 2 and 3, served to separate these two bars fairly well, and they were selected in order to see if the separation could be increased by the use of the alternating current incremental test.

Tests were made in which the value of the constant magnetomotive force, F_F , was varied from 250 to 2500 ampere turns and the alternating magnetomotive force, ΔF , from 250 to 875 ampere turns. Starting with a demagnetized bar each time, F_F was applied and the iron brought into a cyclic condition. Then the alternating ΔF was applied and the reading of the wattmeter noted. The maximum separation between the two bars was found to take place under the following conditions:

1. A constant F_F of 1500 ampere-turns was applied and the specimen brought into a cyclic condition.
2. The constant magnetomotive force, F_F , was then reduced to 750 ampere-turns.
3. Then the alternating incremental force, ΔF , of 700 ampere-turns was applied and the power loss measured.

These preliminary tests on bars *I-10* and *X-26* were made at a frequency of 20 cycles. In the tests on the specimens the above procedure was also used at frequencies ranging from 14 to 30 cycles.

The phase angle of the voltage applied to the electrometer needle was also varied in an attempt to increase the separation between specimens of different heat treatments but without success. The widest separation was obtained with the connections shown in Fig. 4 and using the procedure outlined above.

Before making the alternating current tests, the temperature rise produced by an alternating magnetomotive force acting on a specimen was studied and also the effect of the length upon the loss in the specimens.

Temperature Rise:

The hysteresis and eddy current losses in the specimens under alternating magnetizing forces produce a rise in temperature. In

order to determine the temperature rise that would occur, a specimen, X-9, which had been quenched at 2419°F . (1326°C .) and which had not been drawn, was chosen. This specimen was found by Sanford (6) to have the maximum coercive force of any of the bars tested. It was placed in a 3-in. solenoid and subjected to an alternating magnetomotive force of 7500 ampere-turns at 20 cycles. The temperature rise of the specimen was measured by a thermometer and found to equal 20°C . (68°F .) above room temperature. It required over 2 hours

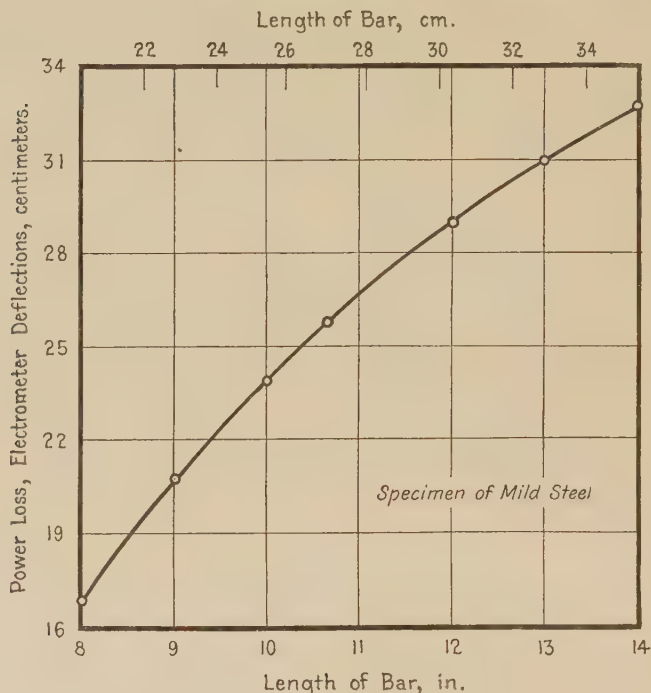


FIG. 5.—Effect of Length on Power Loss.

for the specimen to reach a constant temperature. In the alternating current incremental test a specimen was never in the solenoid for more than a few minutes and any change in loss that took place due to heating was negligible. This statement was verified later when it was found that wattmeter readings did not change even if the specimen was left for several minutes in the solenoid.

Effect of Length of Bars:

The total loss in a specimen of iron under an alternating magnetomotive force is proportional to the volume, hence it was necessary to determine the effect of the lengths of the bars on the loss readings of the wattmeter.

In the alternating current incremental tests the frequency of the alternating ΔF was varied from 14 to 30 cycles. No alternating current potentiometer was available for this range of frequency and therefore it was impossible to measure a component of the induced voltage which would be proportional to the loss as was done by Spooner (2) in his 60-cycle tests.

A bar of mild steel 14 in. (35.56 cm.) long was placed in the solenoid and the loss measured with an alternating current of 1.8 amperes at 20 cycles frequency flowing through the No. 2 winding of the solenoid. The bar was then removed and 1 in. (2.54 cm.) cut from its length and the loss again measured. This procedure was

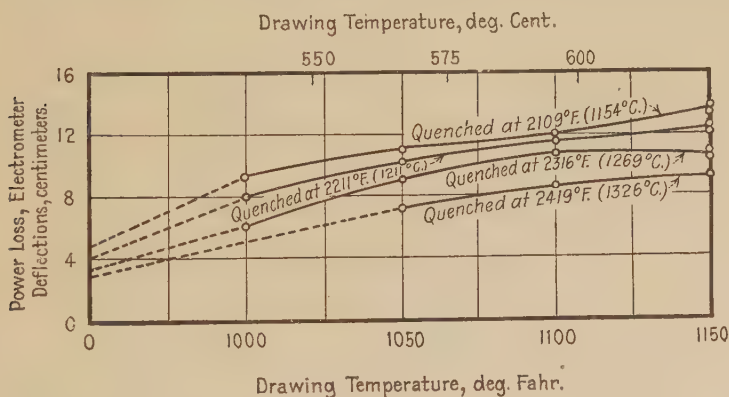


FIG. 6.—Results of Tests on 10-in. (25.4 cm.) Bars at 14.1 Cycles.

repeated until the bar had been reduced to a length of 8 in. (19.32 cm.). The results of this test are shown in Fig. 5, and as was to be expected the effect of length is considerable.

Attempts were made to reduce the readings of loss found for specimens of different lengths to a standard length. This, however, was found to be impossible, and in the incremental alternating current tests the bars were grouped according to their lengths. Thirty of the specimens were nearly exactly 10 in. (25.4 cm.) in length and these were used for the tests. These thirty specimens unfortunately only included two that had been quenched at 2366° F. (1296° C.) and therefore it was not feasible to plot curves for this quench.

Results:

Using the method described above, power loss measurements were made on the 10-in. bars at frequencies of 14.1, 20, and 24.5 cycles, the results of which are plotted in Figs. 6, 7, and 8. Not

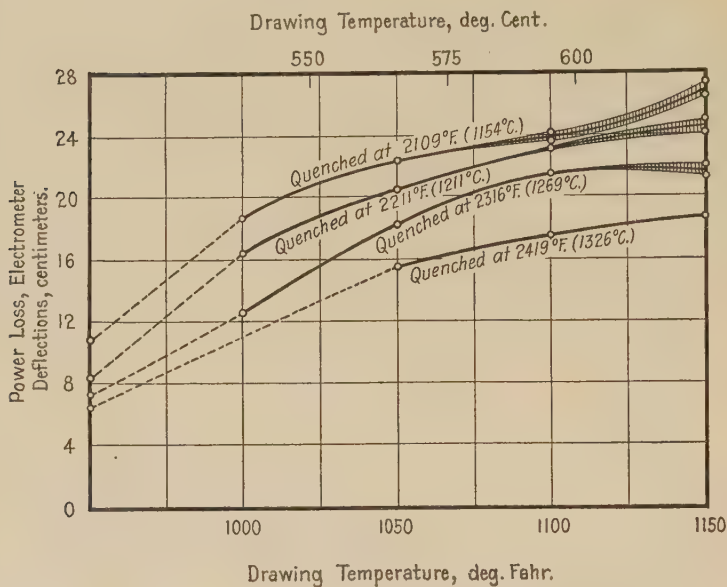


FIG. 7.—Results of Tests on 10-in. (25.4 cm.) Bars at 20 Cycles.

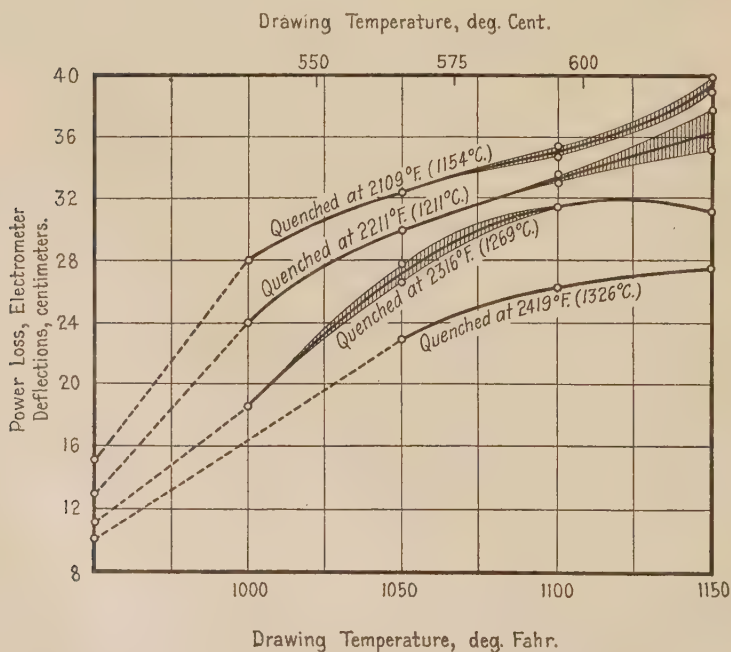


FIG. 8.—Results of Tests on 10-in. (25.4 cm.) Bars at 24.5 Cycles.

more than two bars of any one heat treatment were available in this group, and in most cases only one. The center lines of the cross-hatched areas represent the mean values of the measurements.

These curves are similar in form to those obtained by Spooner (2) in his differential tester with the alternating current potentiometer at

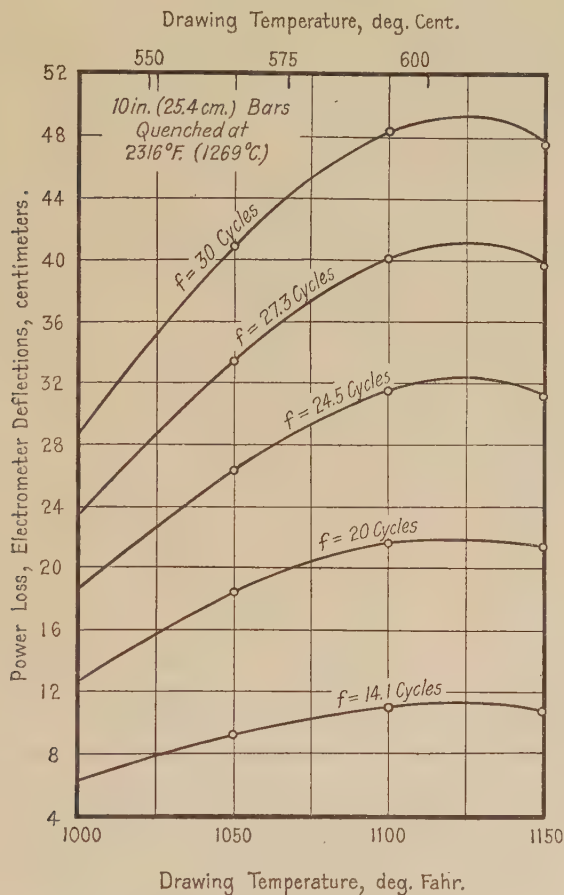


FIG. 9.—Effect of Frequency on Power Loss.

60 cycles frequency. At 14.1 cycles, Fig. 6, the separation between the different quenching temperatures is good, but the curves for any one temperature are quite flat. At 20 cycles, Fig. 7, the separation between the different quenching temperatures is better and the curves are steeper. At 24.5 cycles, Fig. 8, the separation is still better and the curves are steeper than in the two previous figures.

The tendency of the curves for the bars quenched at 2316° F. (1268° C.) to bend over at the higher drawing temperatures may be caused by secondary hardening as pointed out by Spooner (2). A further test was made on these bars at 27.3 and 30 cycles. The results of the power loss measurements on these 2316° F. (1268° C.) bars for the range of frequencies are plotted in Fig. 9. The bending over becomes greater as the frequency is raised.

The second largest group of bars of the same length was that of approximately 9.5 in. (24.2 cm.) which, unfortunately, were of too

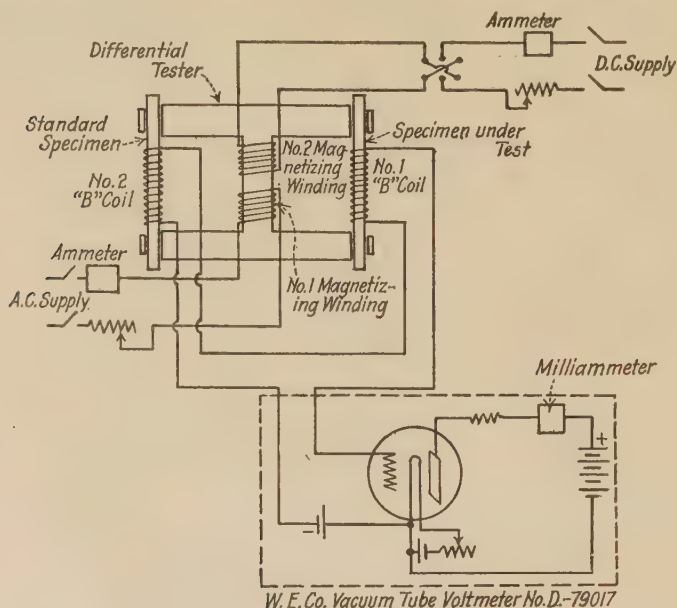


FIG. 10.—Connections for Alternating Current Differential Test.

small a number to give representative curves as were obtained for the 10 in. (25.4 cm.) bars. The power loss in these specimens was measured under the same frequencies and test conditions as described for the 10-in. (25.4 cm.) specimens. Results obtained for these bars were similar to those found for the 10 in. (25.4 cm.) bars.

DIFFERENTIAL ALTERNATING CURRENT INCREMENTAL TEST

In the differential alternating current incremental test, using the special differential magnetic tester, a constant magnetomotive force F_F was applied to winding No. 2, and the alternating current incremental magnetomotive force to the No. 1 winding as shown in Fig. 10. Specimens *I-1* and *X-12*, quenched at 2366° F. (1268° C.) and drawn

at 1100° F. (593° C.) were chosen as the standards and the other bars were referred to them. These bars were chosen as the standards because it had been brought out in previous work^(3,8,10) that this combination of quenching and drawing temperatures represents the best heat treatment for cutting efficiency in the 18-per-cent tungsten

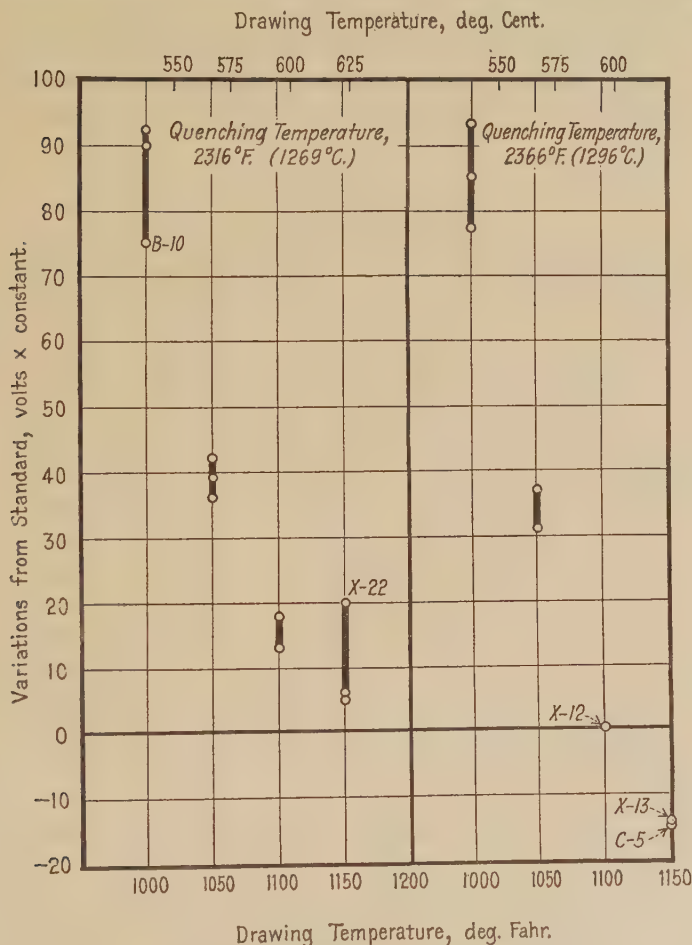


FIG. 11.—Results of Alternating Current Differential Test.

steels. Bar *I-1* was placed in one of the “*B*” coils of the tester and the other bars were placed in turn in the other “*B*” coil, the coils being connected differentially. The difference in voltage induced in the two “*B*” coils under the influence of the alternating current magnetomotive force was measured by a Western Electric Co. vacuum tube voltmeter Type D-79017.

The purpose of this test was mainly to separate bars that had not received the standard heat treatment from those that had.

Test Procedure:

With the standard, bar *I-1* in No. 2 "*B*" coil and the bar under test in No. 1 "*B*" coil, the constant F_F was applied and reversed 12 times to put the bar in cyclic condition. The alternating incremental magnetomotive force was then gradually applied and brought up to

TABLE II.—RESISTIVITY OF SPECIMENS.

Bar	Drawn at		Resistivity, micromhs. per cu. cm.	Bar	Drawn at		Resistivity micromhs. per cu. cm.
	deg. Fahr.	deg. Cent.			deg. Fahr.	deg. Cent.	
BARS QUENCHED AT 2109° F. (1154° C.)				BARS QUENCHED AT 2366° F. (1296° C.)			
A-1.....	<i>a</i>	<i>a</i>	64.0	A-4.....	<i>a</i>	<i>a</i>	73.4
L-11.....	1000	538	56.7	L-1.....	1000	538	61.0
G-5.....	1000	538	50.3	X-6.....	1050	566	59.0
K-8.....	1050	566	48.5	H-4.....	1050	566	57.3
X-5.....	1050	566	52.7	X-12.....	1100	593	57.1
X-23.....	1100	593	53.8	K-1.....	1100	593	50.7
I-11.....	1100	593	50.4	X-13.....	1150	621	57.1
J-14.....	1150	621	48.4				
X-24.....	1150	621	41.6				
BARS QUENCHED AT 2211° F. (1211° C.)				BARS QUENCHED AT 2419° F. (1326° C.)			
K-4.....	<i>a</i>	<i>a</i>	61.7	X-9.....	<i>a</i>	<i>a</i>	74.8
L-7.....	1000	538	57.4	X-11.....	1000	538	59.4
X-14.....	1050	566	55.7	K-2.....	1000	538	57.3
H-10.....	1050	566	55.8	X-15.....	1050	566	60.7
X-20.....	1100	593	55.1	G-2.....	1050	566	58.1
X-26.....	1150	621	53.1	X-2.....	1100	593	56.1
				X-7.....	1150	621	54.5
BARS QUENCHED AT 2316° F. (1268° C.)							
K-3.....	<i>a</i>	<i>a</i>	65.6	X-16.....	1100	593	54.1
L-6.....	1000	538	57.3	X-22.....	1150	621	52.4
X-14.....	1050	566	57.7	J-6.....	1150	621	52.2
C-9.....	1050	566	56.2				

^a No draw.

the desired value. This procedure was found necessary in order to repeat results. The difference in the voltages induced in the two "*B*" coils by the alternating flux in the specimens was then read.

The value of the constant magnetomotive force F_F , was chosen to give a flux density of about 10,000 gauss in the standard specimen. The alternating incremental magnetomotive force used was of such a value as to give an incremental magnetizing force of approximately 20 gilberts per centimeter. Under these conditions there was no appreciable rise in temperature of either specimen. The voltmeter indication obtained with bar *X-12* in the tester was taken as the zero of the instrument and the other bars referred to this.

Results:

Tests were made on those bars which had been quenched at 2316° F. (1268° C.) and 2366° F. (1296° C.), as these bars had shown little separation in the other tests previously described. Measurements were made with alternating incremental magnetomotive forces at 20, 40, 60, and 133 cycles frequency. The best separation occurred at 60 cycles. At 20 and 40 cycles there was no separation and only slight separation at 133 cycles. The results of the tests at 60 cycles are plotted in Fig. 11. A study of this figure shows that there is no overlap between the standard specimens and any of the other specimens tested.

RESISTANCE MEASUREMENTS

The resistances of some of the bars were measured in a Kelvin Double Bridge and the results are given in Table II. Some of the data given in this table were furnished by Mr. Sanford of the U. S. Bureau of Standards. The measurements were made at 68° F. (20° C.).

A study of this table shows that the *K* specimens are in general out of line with others of the same heat treatment; that the check between two bars having the same heat treatment is in the main good; and that at any one quenching temperature there is a decrease in resistance with increase in drawing temperature.

CONCLUSIONS

Erratic Bars:

As stated before, a number of investigators have tested these bars and found some erratic ones, whose magnetic properties do not agree with other bars of supposedly the same heat treatment.

In this investigation the magnetic properties of specimen *B-10* differs widely from bars *L-6* and *G-9* which were supposed to have had the same heat treatment. This confirms de Forest⁽⁴⁾ results on the same bars. Bars *L-6* and *G-9* appear in the direction of a higher quench.

The results of the incremental magnetic tests on the other hand show but little difference between the following pairs of bars: *D-6* and *F-2*; *X-15* and *L-4*; *X-13* and *C-5*; and *G-14* and *B-4*, which were reported out of line by some of the other observers^(3,4,8).

The magnetic properties of specimen *E-1* as found do not check in the positive incremental test with other bars of the same heat treatment. This result agrees with the results of Spooner⁽⁸⁾ and de Forest⁽⁴⁾. In the negative incremental test, however, this bar appears to be properly heat treated.

The different results obtained by the various investigators upon the same bar depends to some extent upon the values of induction at which the tests were made.

Summary:

In this investigation the best results were obtained at high inductions, the separation between the bars being greater in the direct current negative incremental test where a high induction was used than in the positive incremental test. This result also confirms the data obtained by other investigators⁽²⁾.

If the quenching temperature is known, the drawing temperature may be determined fairly accurately by the loss measurement using the solenoid in the alternating current incremental test, except in the case of specimens quenched at 2316° F. (1268° C.), in which case the curve bends over. This test will not differentiate between specimens which have been quenched at 2316° F. (1268° C.) and drawn at 1100° F. (593° C.) and 1150° F. (621° C.).

If either the quenching or drawing temperature is known, the direct current negative incremental test serves to separate the bars fairly well; better than the alternating current solenoid test. Furthermore, if neither the quenching nor drawing temperatures are known, the direct current incremental tests offer a simple and reliable method of locating the specimens according to their heat treatments.

By means of the differential magnetic tester and an incremental alternating current test it is possible to distinguish between the bars that are correctly heat treated and those that are not.

The values of the constant magnetizing force and the incremental magnetizing force used in this investigation apparently are the best for the specimens tested. However, further investigation may develop different combinations of magnetizing forces which may produce better results.

In this work the specimens had two variables: namely, quenching and drawing temperatures; therefore two magnetic characteristics are necessary for differentiating between them. An incremental magnetic test offers a simple means of obtaining the needed magnetic properties.

The incremental tests are easy to apply, quick and reproducible. They offer a new tool for use in magnetic analysis.

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